Direct reaction spectroscopy of exotic nuclei

RNB6, Argonne National Laboratory

22th-26th September 2003

Jeff Tostevin
Department of Physics
School of Electronics and Physical Sciences
University of Surrey
UK

Direct reactions – experimental advances

- Single-nucleon transfer reactions, HRIBF (Thomas), ISOLDE, GANIL (+Tiara array), ANL, TA&M, ….
- Coulomb excitation: RIKEN, MSU, GSI, … (Korten)
- Elastic and inelastic scattering, many groups, …
- Break-up reactions, ND, MSU, RIKEN, GSI ...
- One- and two-nucleon knockout, MSU, GANIL, GSI, RIKEN

Much direct reaction theory 'of old' can be carried over to exotics arena – but the very weakly bound systems were a new challenge (non-perturbative, non-DWBA)

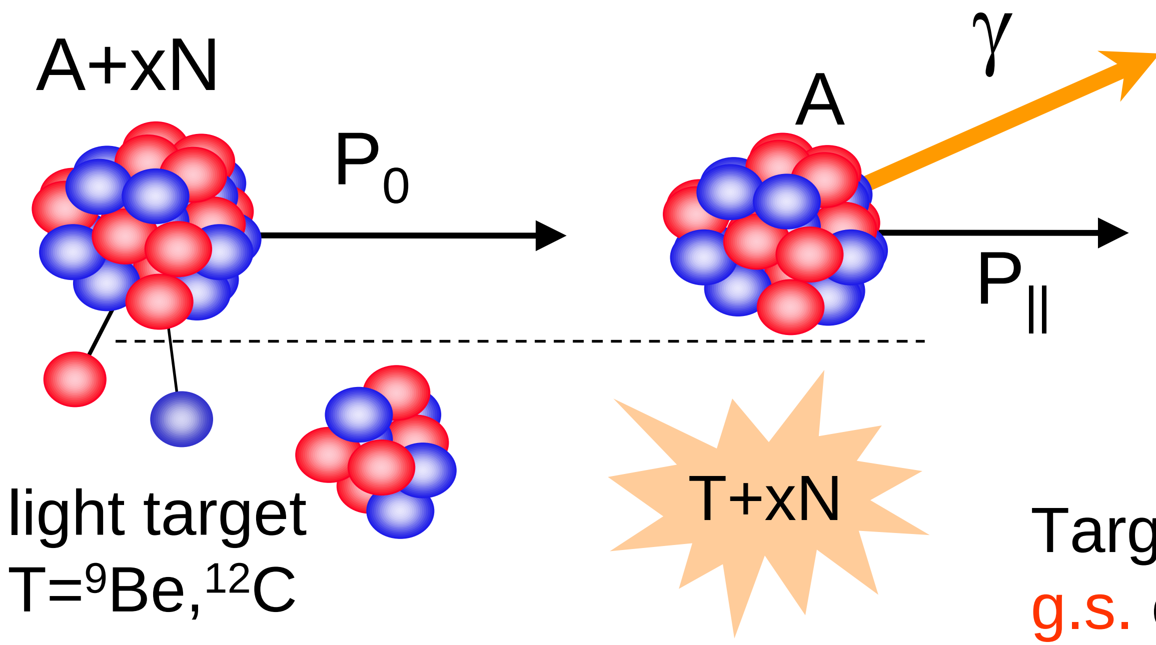
Direct one- and two-nucleon spectroscopy

Consider here progress with:

- Single-nucleon knockout reactions of weak and well-bound states to probe correlations beyond the shell model – short range (hard core), cluster (e.g. alpha particle), tensor, → access to deep hole states
- Core degrees of freedom – core deformation effects
- Core degrees of freedom - one-nucleon overlaps in non-Borromean two-nucleon halo states.
- Two-nucleon correlations observed using direct two-nucleon knockout reactions (Bazin)?

One- and two-nucleon knockout reactions

Peripheral collisions (E ≥ 50A MeV; MSU, RIKEN, GSI)



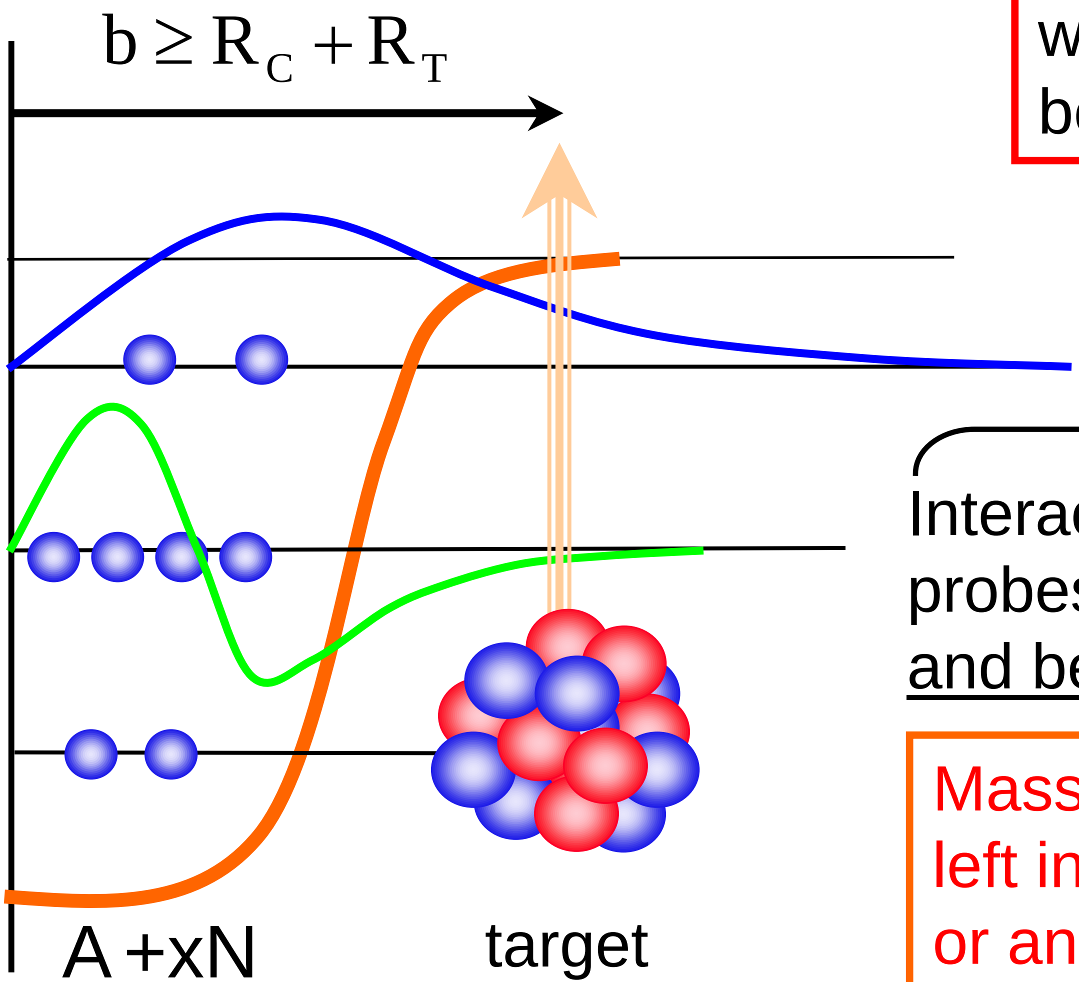
only heavy mass A residue is detected, <u>with</u> coincident γ-ray detection

Target T left in g.s. or excited state

<u>Direct from the projectile perspective</u>

Events contributing will be both <u>break-up</u> and <u>stripping</u> both of which leave a mass A residue in the final state

Probe the surface and tails of wave functions



with sensitivity to both ℓ and κ

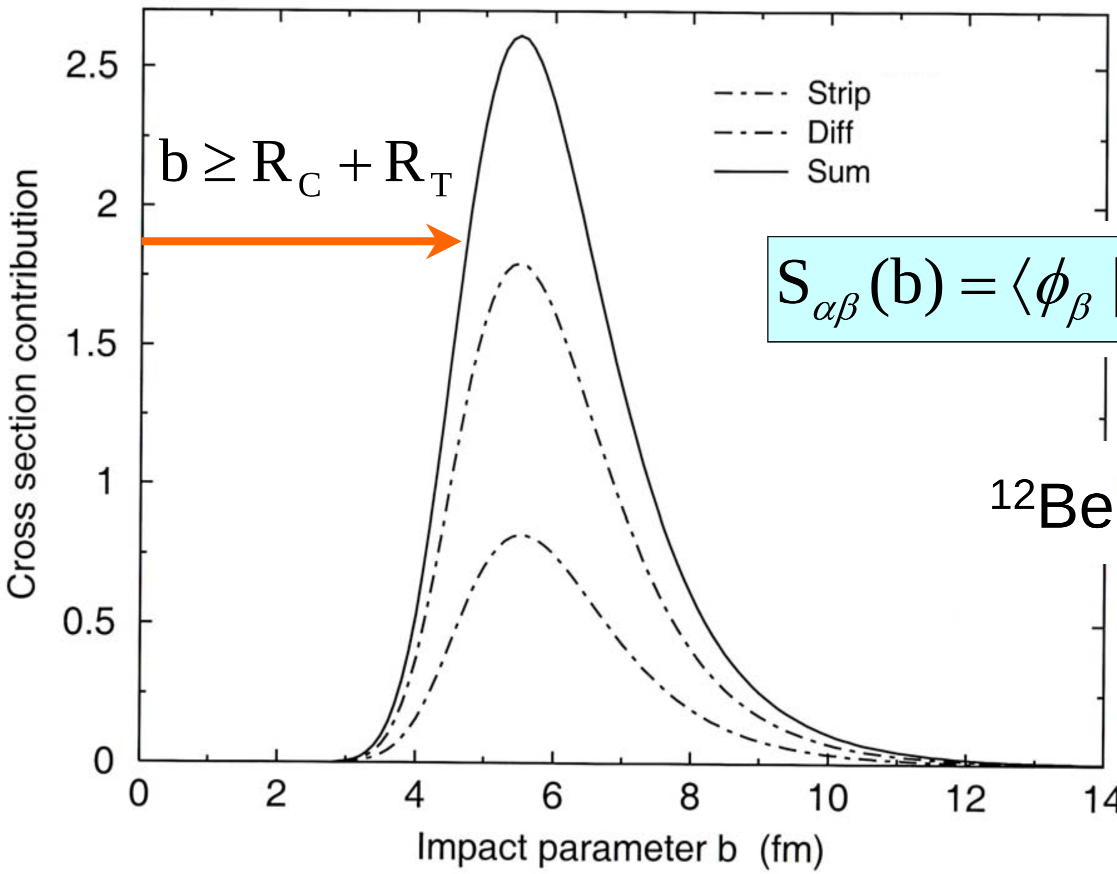
$h_\ell(i\kappa r)$

Interaction with the target probes $\phi_0(\mathbf{r})$ <u>at surface and beyond</u> $b \ge R_C + R_T$

Mass A residue will be left in the ground state or an excited state

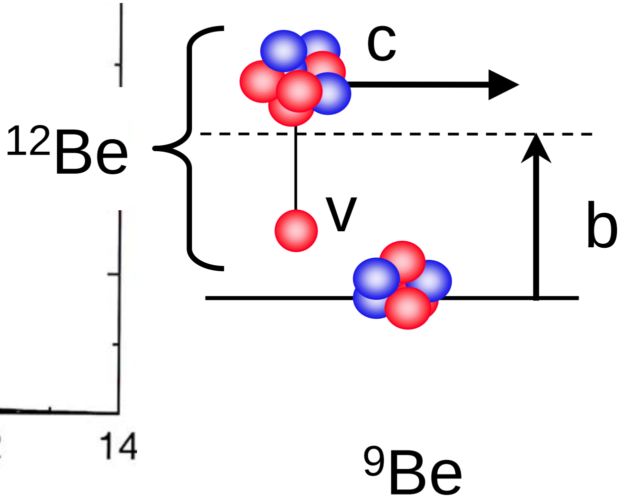
Contributions are from surface and beyond

$^{12}Be + ^{9}Be \rightarrow ^{11}Be(gs) + X$, 80A MeV



Eikonal reaction theory

$$S_{\alpha\beta}(b) = \langle \phi_\beta \mid S_c(b_c)\, S_v(b_v) \mid \phi_\alpha \rangle$$

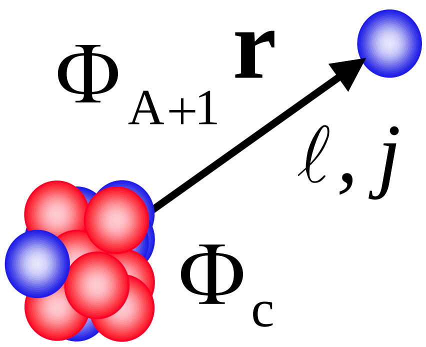


UniS

Structure information – overlap integrals

Nucleon removal from Φ_{A+1} will leave mass A residue in the ground or an excited state - even in extreme sp model

More generally: amplitude for finding nucleon with sp quantum numbers ℓ,*j*, about core state Φ_c in Φ_{A+1} is



$$F^c_{\ell j}(\mathbf{r}) = \langle \mathbf{r}, \Phi_c \,|\, \Phi_{A+1} \rangle, \; S_N = E_{A+1} - E_c$$

$$\int d\mathbf{r}\, |F^c_{\ell j}(\mathbf{r})|^2 = C^2 S(\ell j)$$

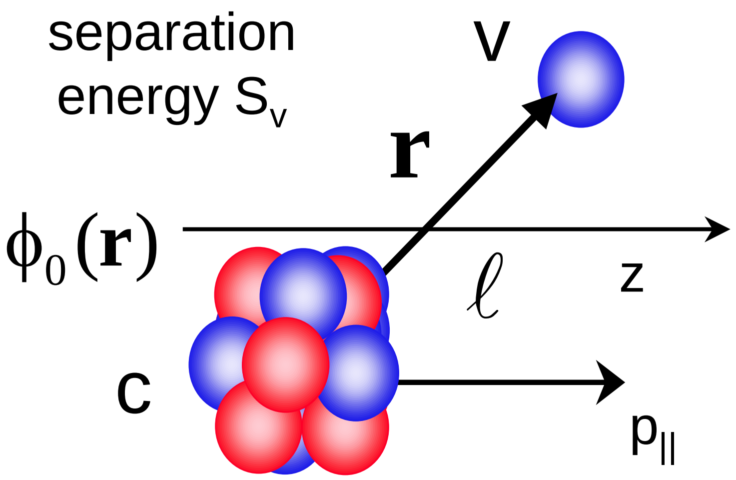
Spectroscopic factor - occupancy of the state

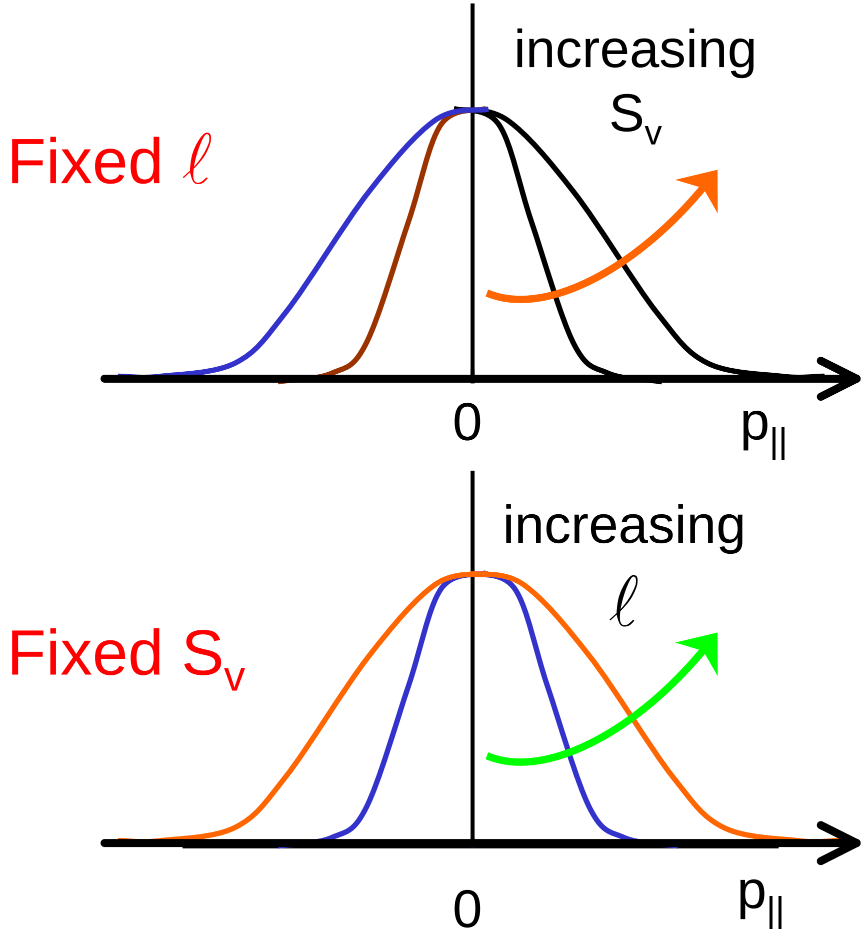
Usual to write

$$F^c_{\ell j}(\mathbf{r}) = \sqrt{C^2 S(\ell j)}\; \phi_0(\mathbf{r}); \qquad \int d\mathbf{r}\, |\phi_0(\mathbf{r})|^2 = 1$$

with $\phi_0(\mathbf{r})$ calculated in a potential model (Woods-Saxon)

Measurement of the momentum content

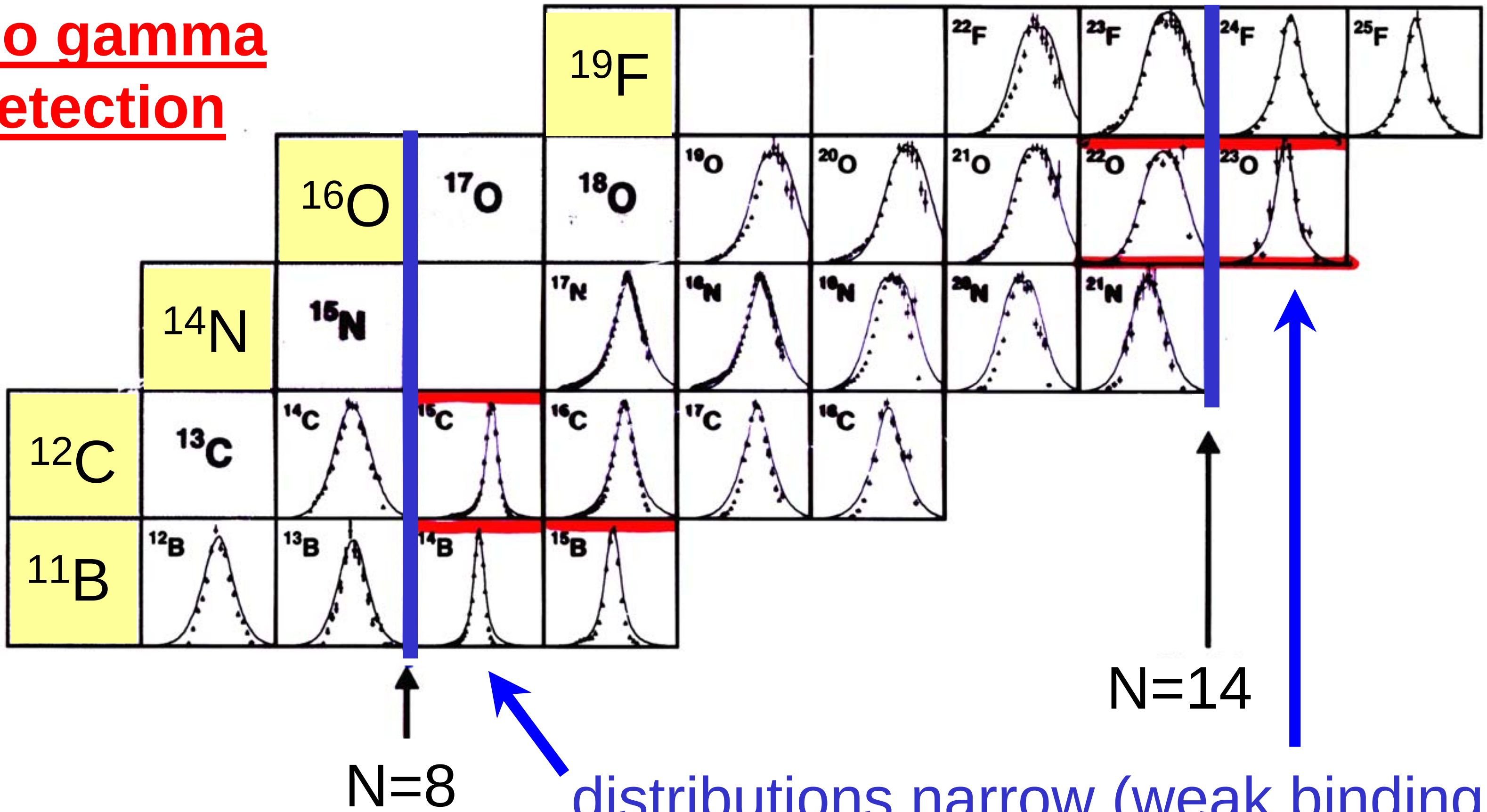




consider momentum components $p_{||}$ of the heavy residue parallel to the beam direction. In the projectile rest frame ……………

Systematics of momentum content in p-shell

No gamma detection



distributions narrow (weak binding or s-states as one crosses shell or sub-shell closures

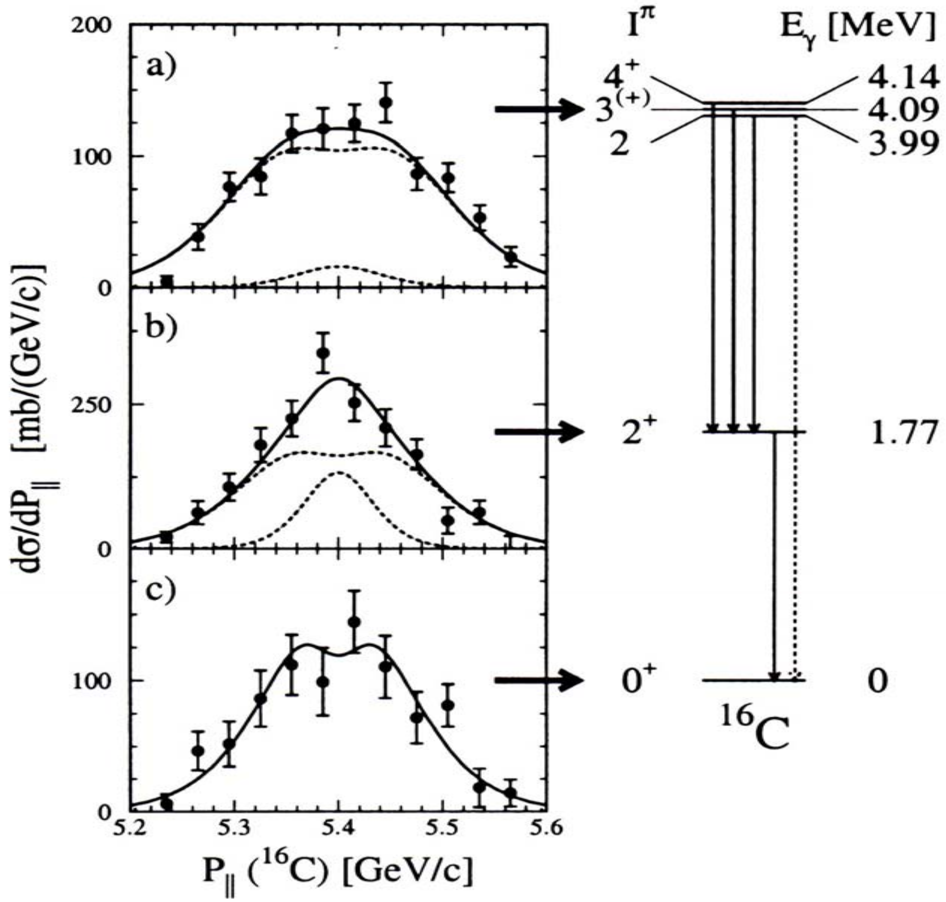
E.Sauvan et al., Phys Lett B **491** (2000) 1

Single-neutron knockout from ^{17}C - eikonal

ℓ=0,2
admixture

ℓ=0,2
admixture

pure ℓ=2
<u>but large</u>!!

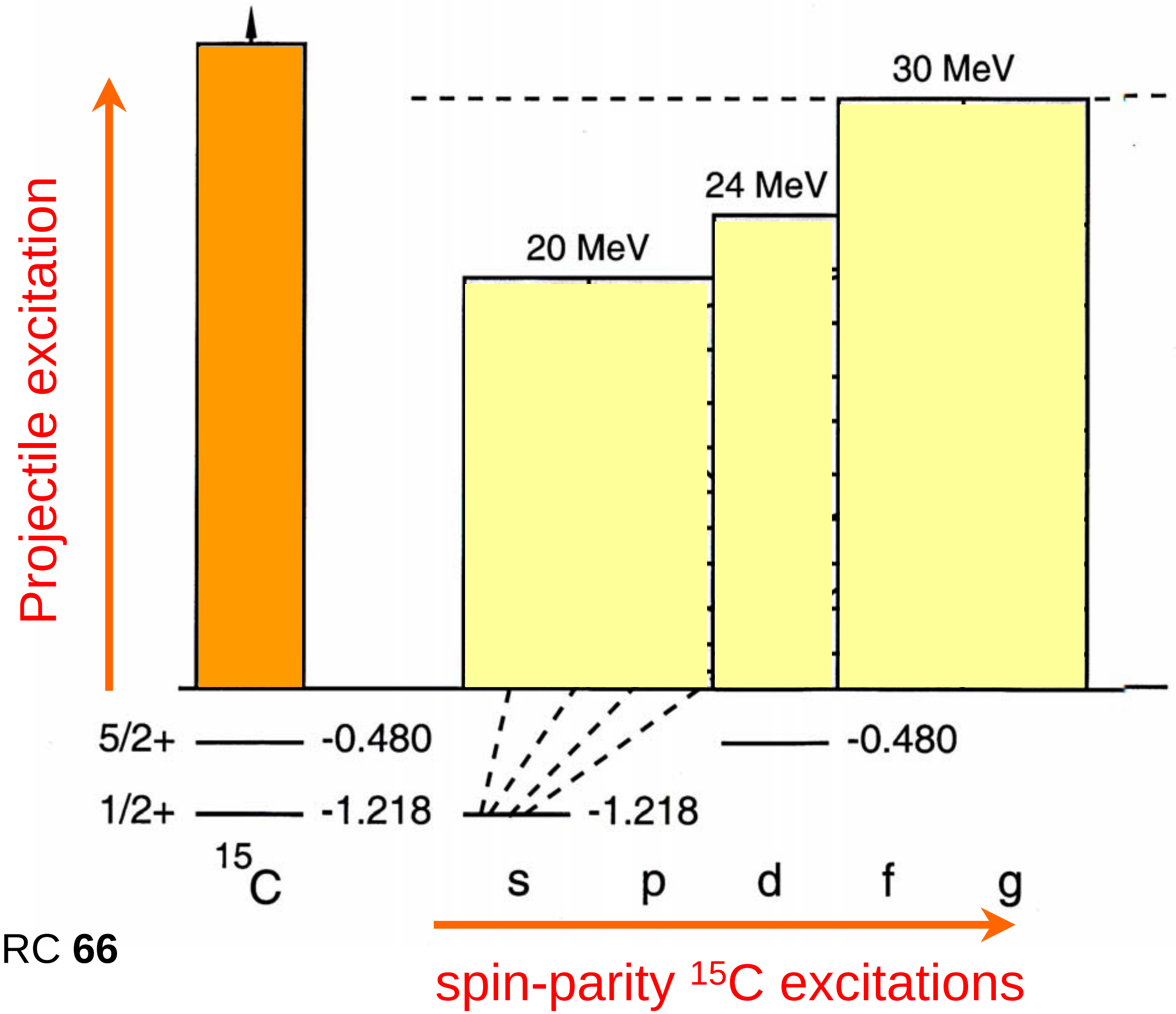


$$\sigma(nI^{\pi}) = \sum C^2 S(j, nI^{\pi})\, \sigma_{sp}(j, B_n)$$

V. Maddalena et al. Phys. Rev. C **63** (2001) 024613

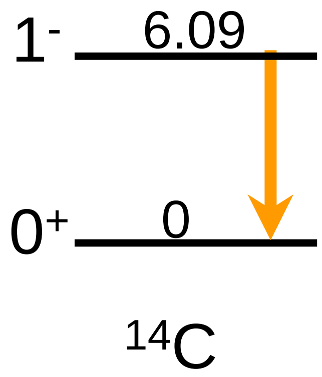
Coupled channels model – beyond eikonal

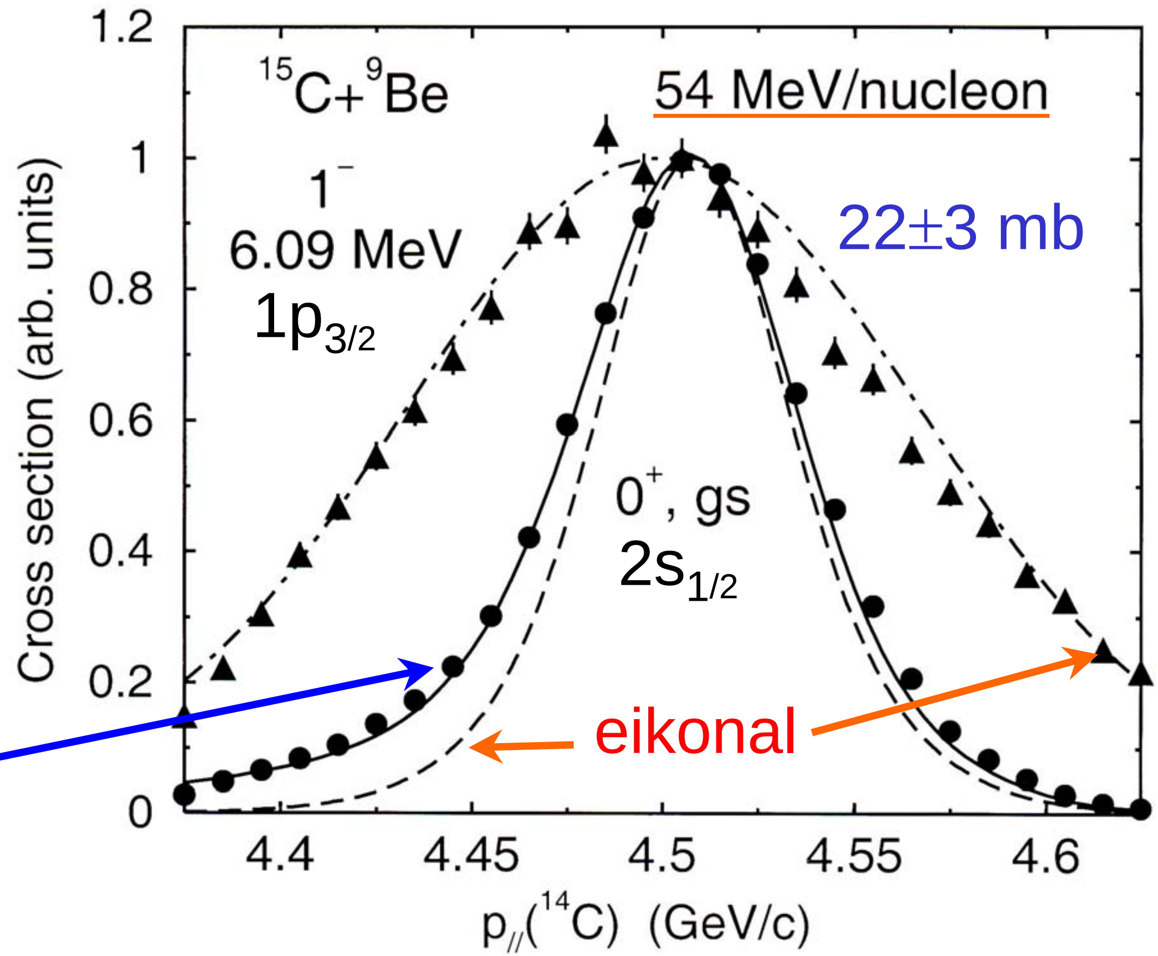
Example of a coupled channel (CDCC) model space for ^{15}C break-up on a ^{9}Be target at E= 54A MeV



J.A. Tostevin et al, PRC **66** (2002) 024607

Non-adiabatic and non-eikonal effects for ^{15}C



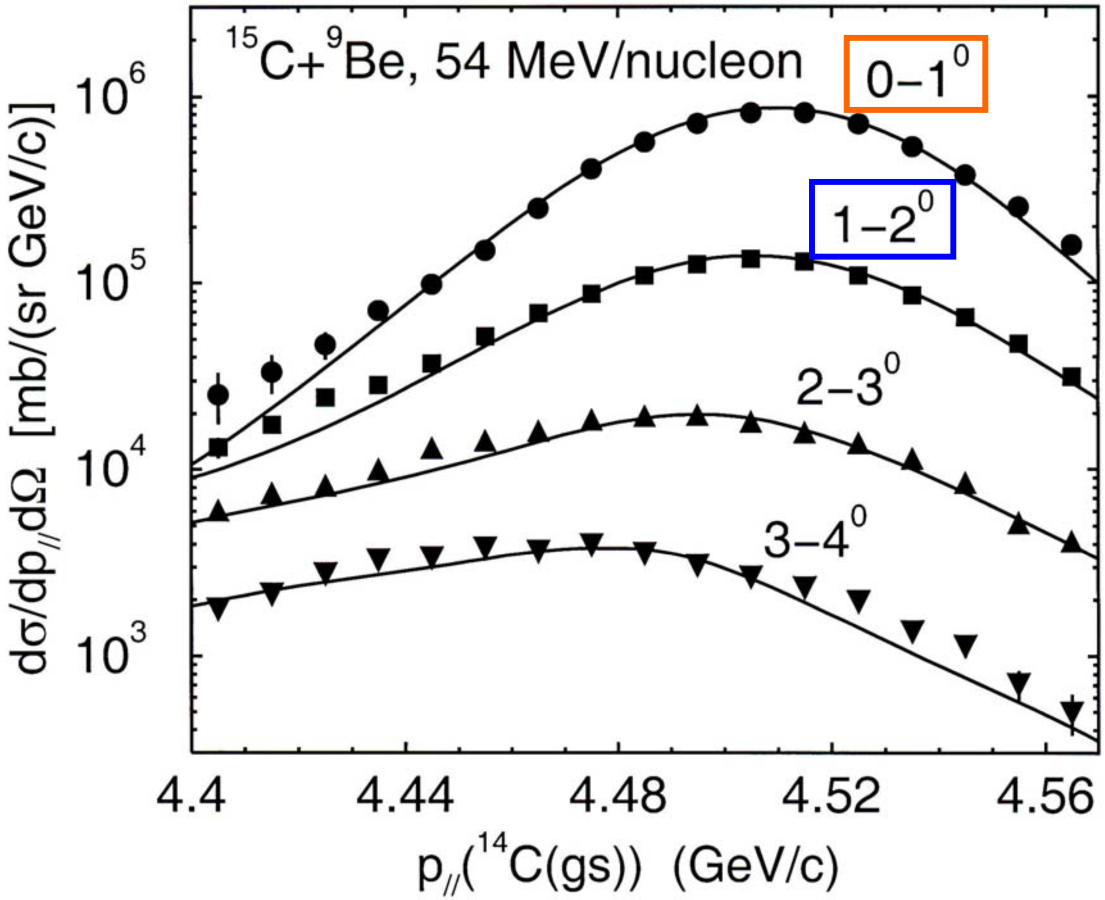


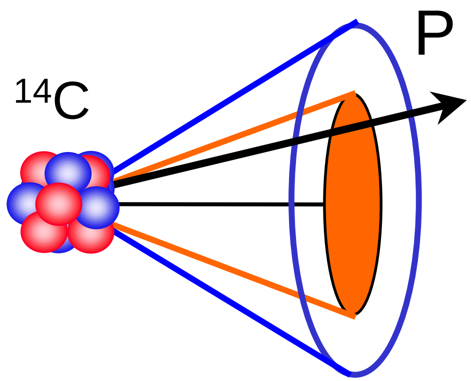
Coupled channels (CDCC) 109±13 mb

J.A. Tostevin et al, PRC **66** (2002) 024607

$^{9}Be\,(^{15}C, ^{14}C(I^{\pi}))\,X$

Core fragment differential cross sections





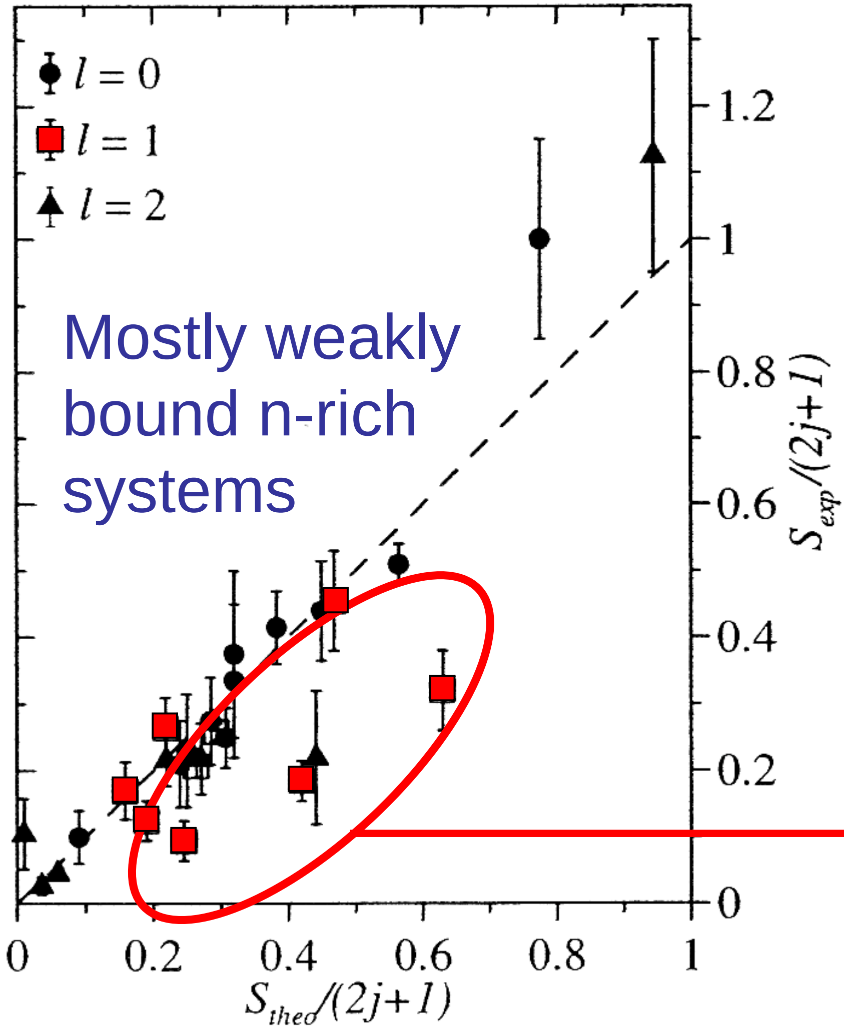
these yields almost entirely due to diffractive dissociation

$^{9}Be\ (^{15}C,^{14}C(gs))\ X$

J.A. Tostevin et al, PRC **66** (2002) 024607

UniS

Deduced vs. shell model spectroscopic factors



Can define reduction factor

$$R_s = \frac{\sigma_{\exp t}}{\sigma_{th}} \leq 1$$

th ≡ Shell model structure plus eikonal reaction

More bound systems

P.G. Hansen and J.A.Tostevin, ARNPS **53** (2003), 219

UniS

Absolute spectroscopic factors using knockout

B.A. Brown et al. PRC **65** (2002) 061601(R)

^{A-1}Z	E_B MeV/ nucleon	E^*	σ_{sp}(mb) [a] Strip.	Diffr.	σ_{th} (mb)	σ_{expt} (mb)	R_s
^{11}B	250	a	21.9	1.8	100.5	65.6(26) [b]	0.65(3)
	1050	a	20.8	1.9	96.1	48.6(24) [c]	0.51(3)
	2100	a	20.6	2.0	96.1	53.8(27) [c]	0.56(3)
^{11}C	250	a	21.4	1.7	98.2	56.0(41) [b]	0.57(4)
	1050	a	20.2	1.8	93.4	44.7(28) [c]	0.48(3)
	2100	a	20.1	1.9	93.3	46.5(23) [c]	0.50(3)
^{15}N	2100	0	15.40	1.77			
		6.324	12.95	1.30			
		Sum			80.2	54.2(29) [b]	0.68(4)
^{15}O	2100	0	14.63	1.61			
		6.176	12.54	1.23			
		Sum			76.9	42.9(23) [c]	0.56(3)

(e,e'p)

S_p=15.96 → 0.53(2) | 0.51(3)

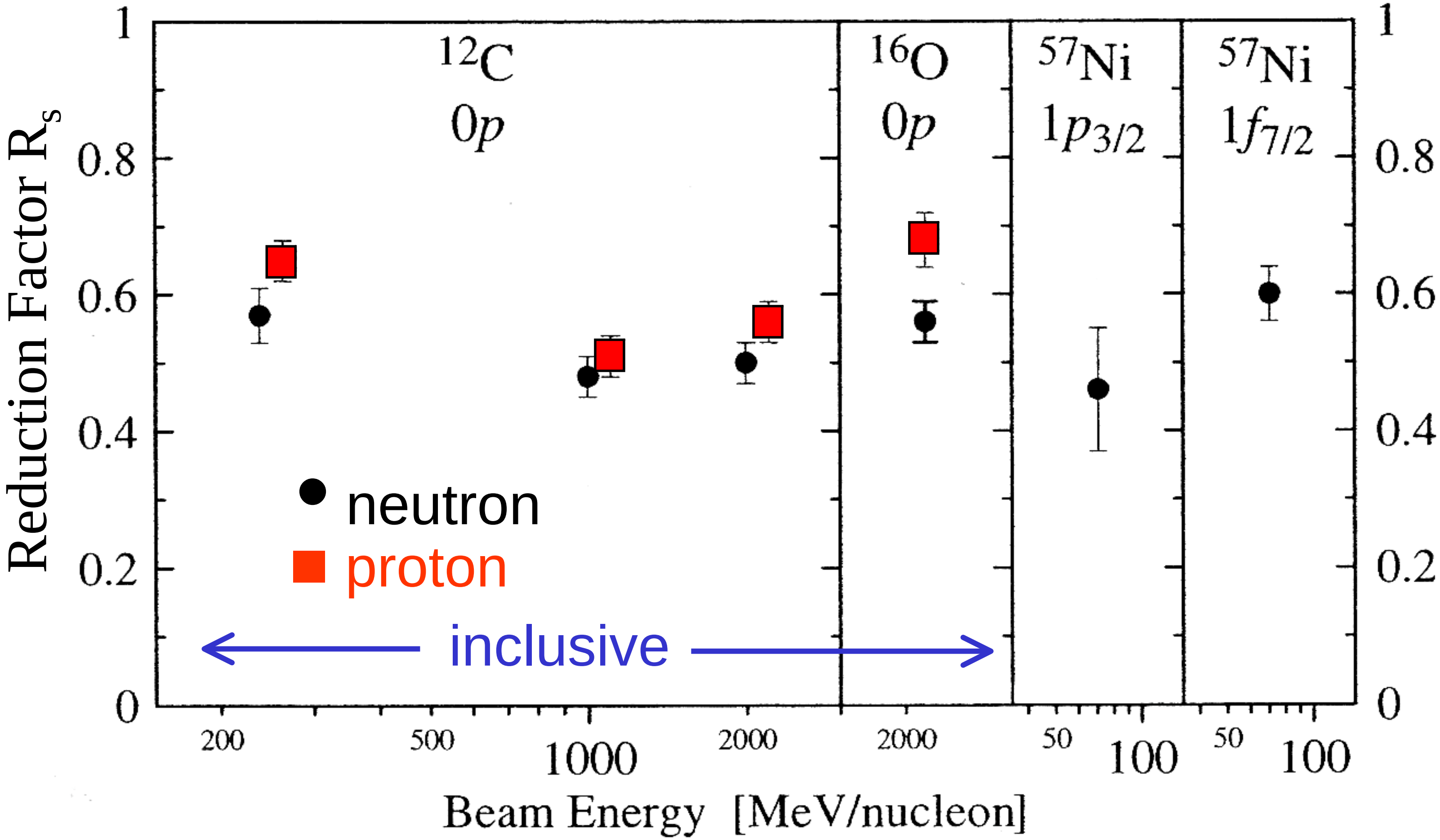
S_n= 18.72 → 0.49(2)

S_p= 12.13 → 0.68(4) | 0.67(5)

S_n= 15.66 → 0.56(3)

UniS

More strongly bound states – deep hole states

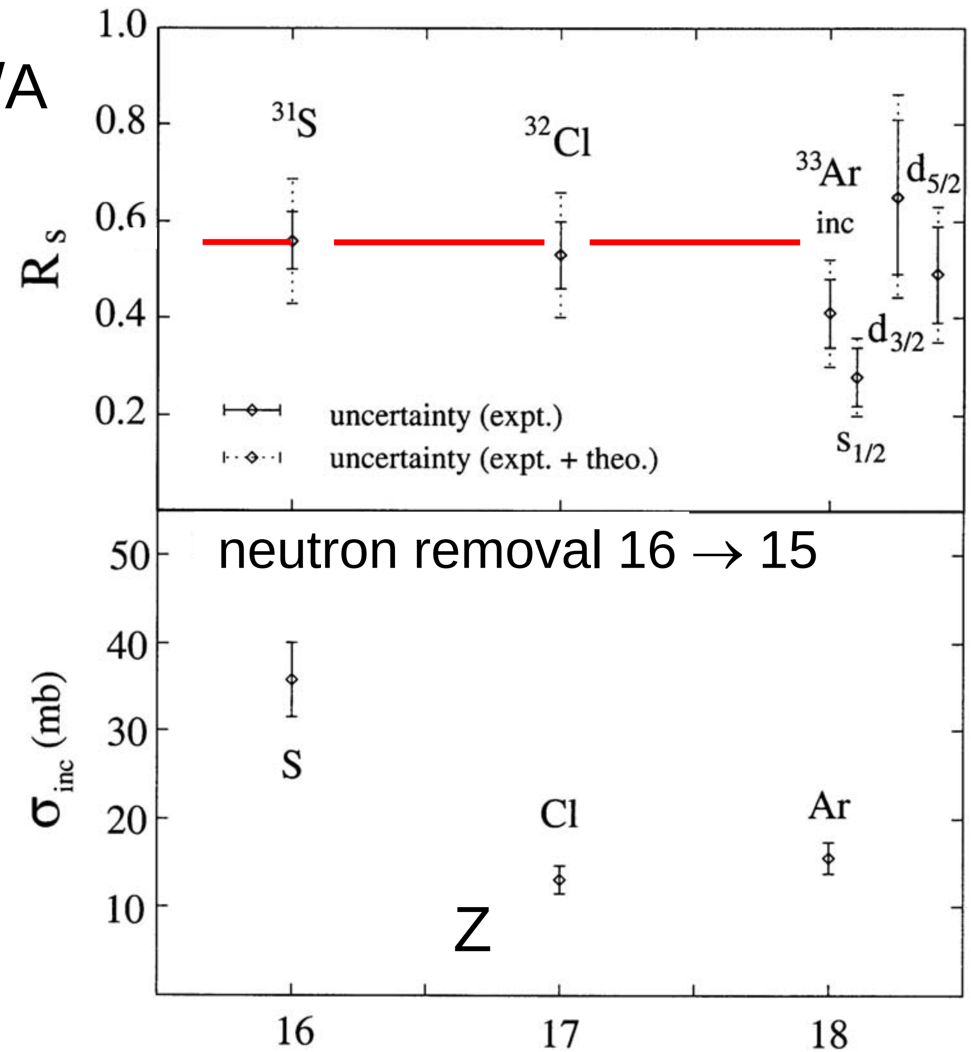


P.G. Hansen and J.A.Tostevin, ARNPS **53** (2003), 219

UniS

Neutron removal from the N=16 isotones

E_{beam} = 63, 66, 70 MeV/A



<u>Deep hole-states:</u>

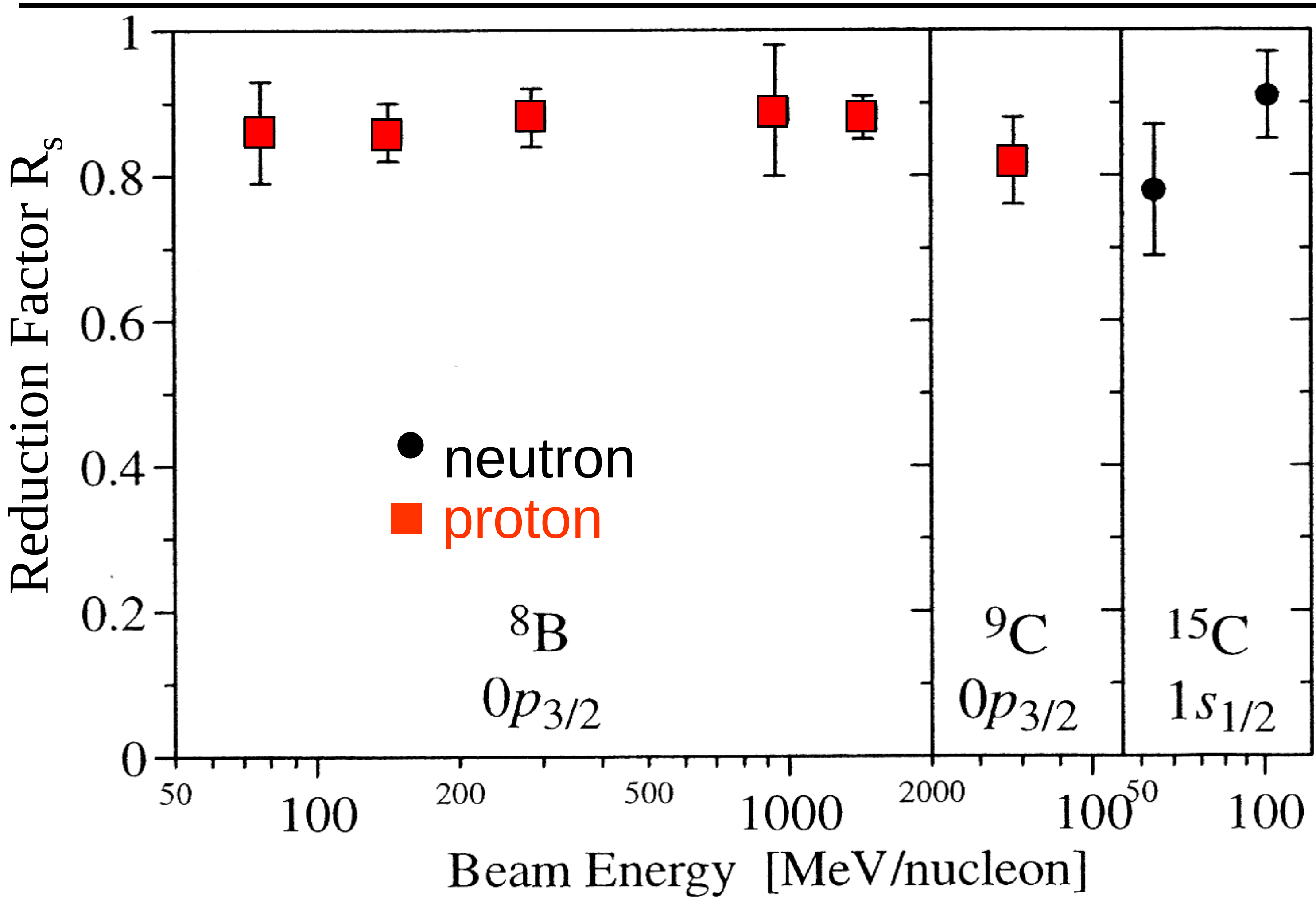
$S_n(^{32}S)$ = 15.04 MeV

$S_n(^{33}Cl)$ = 15.74 MeV

$S_n(^{34}Ar)$ = 17.07 MeV

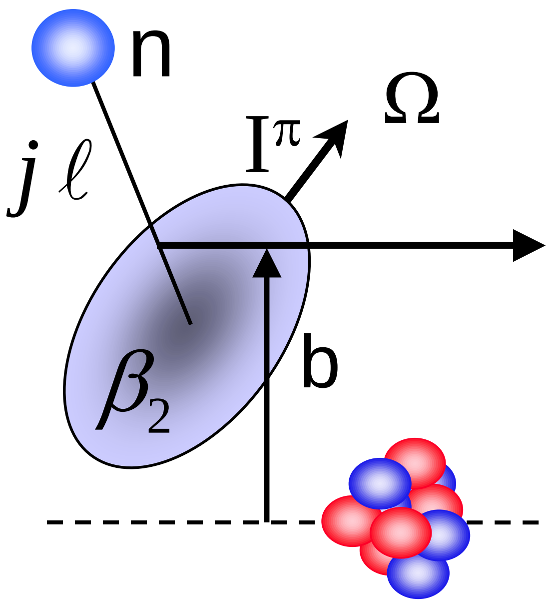
Alexandra Gade et al,
Submitted to PRC, MSU preprint

Weakly bound states – with good statistics



P.G. Hansen and J.A.Tostevin, ARNPS **53** (2003), 219

Core degrees of freedom – deformed cores



$$\Psi_{JM}(\mathbf{r},\hat{\Omega}) = \sum_{\ell\, j\, I} [\phi_{j\ell}(\mathbf{r}) \otimes \phi_I(\hat{\Omega})]_{JM}$$

$$I = 0, 2, 4, \ldots\ldots.$$

weak-coupling n-deformed core model:
this includes

- core excitation / de-excitation
- core reorientation effects

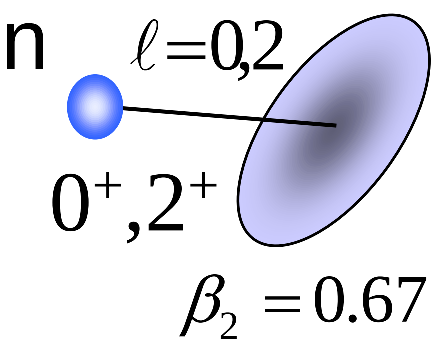
The inclusive stripping contribution now reads, e.g.

$$\sigma_{\mathrm{strip}} = \sum_M \int d\mathbf{b} \int d\hat{\Omega}\, \langle \Psi_{JM} \,||\, \mathrm{S_c}(\hat{\Omega})|^2\, (1-|\mathrm{S_n}|^2)\,|\, \Psi_{JM} \rangle$$

P.Batham, J.A. Tostevin and I.J. Thompson, in preparation,2003

Core deformation effects –outstanding cases

$^{11}Be(1/2+)$: $S(0^+)=0.76$, $S(2^+)=0.18$



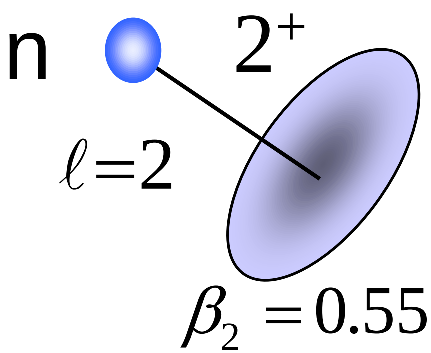
excess of cross section to $^{10}Be(2^+)$ state

$\sigma_{exp}(2^+)$= 16(4) mb, $\sigma_{th}(2^+)$= 9 mb

σ_{diff}(deformed) increased by 8 mb

T. Aumann et al., PRL **84** (2000) 35

$^{17}C(3/2^+)$: $S(2+,\ell=2)=1.44$, $S(2+,\ell=0)=0.16$, $S(0^+,\ell=0)=0.03$



excess of cross section to $^{16}C(0^+)$ state

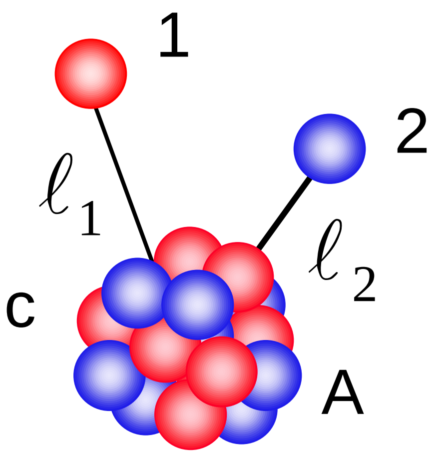
$\sigma_{exp}(0^+)$= 22(11) mb, $\sigma_{th}(0^+)$= 2 mb

σ_{diff} (deformed) increased by 19.4 mb

V. Maddelena et al., PRC **63** (2001) 024613

Direct two nucleon knockout – 2N correlations?

$$\sigma_{\text{strip}} = \sigma_{-2\text{N}} = \int d\mathbf{b}\ \langle \phi_0 \,||\, S_c|^2 \,(1-|S_1|^2)(1-|S_2|^2)\,|\,\phi_0\rangle$$



Estimate assuming removal of a pair of <u>uncorrelated</u> nucleons -

$$\phi_0(A,\mathbf{r}_1,\mathbf{r}_2) = \Phi_c(A)\phi_{\ell_1}(\mathbf{r}_1)\phi_{\ell_2}(\mathbf{r}_2)$$

$$\boxed{\sigma_{\text{strip}} \Rightarrow \sigma_{\text{strip}}(\ell_1\ell_2)}$$

contribution from direct 2N removal $\sigma_{-2\text{N}}$

p particles ℓ_α

q particles ℓ_β

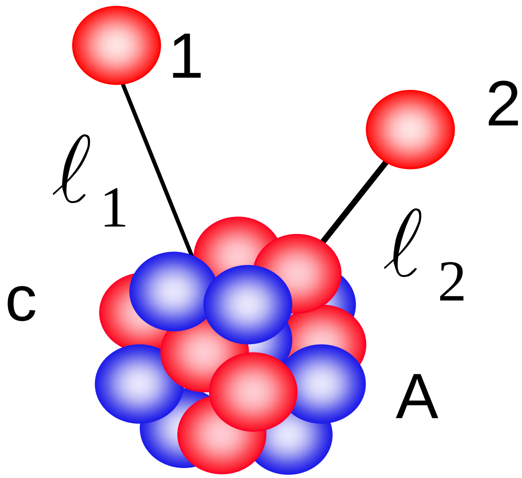
$$\boxed{\begin{aligned}\sigma_{-2\text{N}} &= \frac{p(p-1)}{2}\sigma_{\text{strip}}(\ell_\alpha\ell_\alpha) + \frac{q(q-1)}{2}\sigma_{\text{strip}}(\ell_\beta\ell_\beta)\\ &+ pq\,\sigma_{\text{strip}}(\ell_\alpha\ell_\beta)\end{aligned}}$$

D. Bazin et al., PRL **91** (2003) 012501

Two proton removal from n-rich – (i) uncorrelated

$^{28}Mg \rightarrow {}^{26}Ne$(inclusive)

D. Bazin et al., PRL **91** (2003) 012501



Assuming $(1d_{5/2})^4$ then

$$\sigma_{-2N} = \frac{4(4-1)}{2}\sigma_{strip}(22) \approx 1.8\text{mb}$$

Expt:1.50(1)mb

$$\boxed{\sigma_{strip}(22) = 0.29 \text{ mb}}$$

$$\sigma_{strip}(02) = 0.32 \text{ mb}$$

$$\sigma_{strip}(00) = 0.35 \text{ mb}$$

p=4

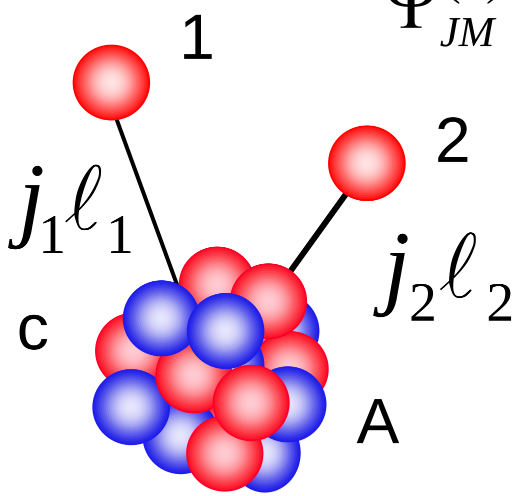
$$\ell = 2, \ \frac{p(p-1)}{2} = 6$$

Two proton removal from n-rich – (ii) correlated

$$\sigma_{\text{strip}} = \frac{1}{2J+1}\sum_{M\,c}\int d\mathbf{b}\ \langle \Psi_{JM}^{(c)} \,||\, \mathrm{S}_c|^2\,(1-|\mathrm{S}_1|^2)(1-|\mathrm{S}_2|^2)\,|\,\Psi_{JM}^{(c)}\rangle$$

$$\Psi_{JM}^{(c)} = \sum_{\alpha\, I} C_{\alpha}^{JIc}[\overline{[\phi_{j_1\ell_1}(1)\otimes\phi_{j_2\ell_2}(2)]}_I\otimes\phi_c]_{JM}$$

$$\alpha \equiv (j_1\ell_1,\, j_2\ell_2)$$



^{28}Mg $\rightarrow$ ^{26}Ne(0^+)

$C(2s_{1/2})^2$	=	– 0.305
$C(1d_{3/2})^2$	=	– 0.301
$C(1d_{5/2})^2$	=	– 1.05

There is now no factorisation!!

Test case - earlier data from Berkeley (~10%)

2N removal from ^{12}C
B.A. Brown, 2N amplitudes

Kidd et al., Phys Rev C **37** (1988) 2613

Energy/nucleon	250 MeV	1.05 GeV	2.10 GeV
$^{12}C \rightarrow {}^{10}Be$ (2p) S(2p)=27.18 MeV	**5.82 mb** **5.88(90)**	**5.33 mb** **5.30(30)**	**5.15 mb** **5.81(29)**
$^{12}C \rightarrow {}^{10}C$ (2n) S(2n)=31.84 MeV	**4.26 mb** **5.33(81)**	**3.91 mb** **4.44(24)**	**3.84 mb** **4.11(22)**

J.A. Tostevin, G. Podolyák, et al., in preparation

Cross sections – correlated and uncorrelated

$^{28}Mg \rightarrow ^{26}Ne(0^+, 2^+, 4^+)$ $S = \sigma(\text{in mb}) / 0.29$

	S_{th} unc.	S_{exp}	S_{th} corr.	σ_{exp} (mb)	σ_{th} (mb)
0^+	1.33	**2.4(5)**	**1.72**	0.70(15)	0.53
2^+	1.67	**0.3(5)**	**0.51**	0.09(15)	0.16
4^+	3.00	**2.0(3)**	**1.69**	0.58(9)	0.52
2^+	-	**0.5(3)**	**0.73**	0.15(9)	0.22

Inclusive cross section (in mb) **1.5(1)** **1.43**

J.A. Tostevin, G. Podolyák, et al., in preparation

We have made considerable progress

- Knockout does appear to us the same information as (e,e′p) reactions – <u>but also for neutrons and exotics</u>
- More <u>systematics</u> are confirming this – a new way to study short range, tensor and other correlations in systems with very different structures and binding
- Core deformation effects are significant: specific cases
- Possible to observe new (pre-asymptotic) behaviour of overlap integrals of <u>non-Borromean</u> halo systems? – affect deduced dripline spectroscopy on a detailed level
- Well chosen two-nucleon knockout reactions are <u>direct reactions</u> and <u>can</u> probe 2N correlations (Bazin)